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A.C. TRACTION MOTORS

FOR LOCOMOTIVES

BROWN-BOVERI TRM INDUSTRIES INC.

MAY 1982

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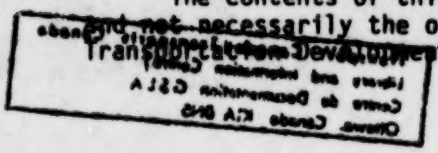

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17. Abstract

This report summarizes the relationships that need to be considered when applying 3-phase A.C. traction technology to North American diesel-electric locomotives. Analysis and computer simulations established the feasibility of a 3-phase A.C. traction motor capable of satisfying North American railway requirements. A technical definition has been developed to describe the "standard" North American motor.

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17. Résumé

Ca rapport établit un sommaire des points à considérer lorsqu'on applique la technologie CA-3 phase à des locomotives diesel-electriques Nord Americaines. Les analyses menées et les calculs sur ordinateur ont démontré la possibilité d'avoir un moteur CA-3 phase capable de satisfaire les exigences des chemins de fer Nord Americains. On a developpé une definition technique d'un moteur Nord Americain "standard".

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PREFACE

Brown Boveri TRM Industries Inc. contracted with the Transportation Development Centre (TDC) to perform work leading to a technical definition of a 3-phase A.C. traction motor suitable for North American locomotive service. This report summarizes the work carried out.

The author wishes to thank Mr. Maurice Audette, TDC Project Officer, for his guidance in performing this study, and the staff of BBC-Lachine, BBC-Mannheim, and BBC-Vienna for their participation. Special acknowledgement is made to Mr. J. Fischer of BBC-Mannheim in the AC-DC-AC system area and Mr. F.T. McInerney in the truck analysis area for their significant contributions to this study.

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SYMBOLS USED IN TEXT

Formulas given in the text are in the rationalized MKS system and conversion factors must be applied, in some cases, in order to use the units shown below.

SYMBOL	UNIT	SIGNIFICANCE	FIRST APPEARS
V_{max}	km/h	maximum locomotive speed (overspeed trip)	pg. 5
μ_{max}	-/-	assigned maximum coefficient of adhesion	5
F_{rtg}	kN	locomotive tractive effort at V_{rtg}	5
W	t	nominal axle loading	5
C	-/-	number of driven axles	5
V_{rtg}	km/h	minimum speed for maintaining full engine power for traction	5
N	kW	maximum engine power available to alternator for traction	5
η_T	-/-	power train efficiency	5
$\bar{F}_{rtg}$	kN	tractive effort per axle at V_{rtg}	5
M_{rtg}	kNm	motor rated torque	6
d_o	mm	wheel diameter (new)	6
i	-	gear reduction	6
Z_1	-	number of teeth on main gear	6
Z_2	-	number of teeth on pinion gear	6
m	mm	gear module	7
D	mm	main gear diameter at pitch circle	7

SYMBOL	UNIT	SIGNIFICANCE	FIRST APPEARS
a	mm	wheel wear (on diameter)	pg. 7
b	mm	clearance between top-of-rail and bottom of gearbox	7
c	mm	tooth height, clearance in gearbox, gearbox thickness (all on diameter)	7
d	mm	motor diameter	7
d_w	mm	axle diameter	7
d_t	mm	motor installation length available in truck	7
U_{max}	V	maximum achievable motor terminal voltage	8
U_{rtg}	V	motor terminal voltage at speed V_{rtg}	8
f	Hz	motor applied frequency	8
f_2	Hz	motor slip frequency	8
U	V	motor applied terminal voltage	9
f_T	Hz	inverter pulse frequency	9
f_{Tmax}	Hz	maximum inverter pulse frequency	9
n	RPM	motor rotational speed	10
n_{axle}	RPM	axle rotational speed	10
n_{max}	RPM	maximum motor rotational speed	10
p	-	number of motor poles	10
WT_i	-	weight transfer coefficient i-th axle	11
ΔW_i	t	axle loading increment i-th axle	11
$\bar{F}$	kN	nominal tractive effort per axle	11
H	mm	force application height	12

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SYMBOL	UNIT	SIGNIFICANCE	FIRST APPEARS
s_m	-	mechanical slip between wheel and rail	pg. 12
$\mu(s_m)$	-	coefficient of adhesion as function of mechanical slip between wheel and rail	12
$W_{eff\ i}$	t	instantaneous axle loading i-th axle	12
V_{wheel}	km/h	linear wheel speed	12
$V_{locomotive}$	km/h	locomotive ground speed	12
$F_{nominal}$	kN	nominal per-axle tractive effort	12
s_e	-	electrical slip in motor	13
$V_{synchronous}$	km/h	locomotive ground speed equivalent of rotating field	13

1.0 SUMMARY

BBC Brown Boveri Canada has developed a concept for an AC-DC-AC propulsion system suitable for use with North American diesel-electric locomotives with power ratings of up to 4000 hp. Because of the heavier axle loadings, more severe environmental conditions, and differing railway maintenance and operating procedures in North America as compared to Europe, the traction motor was known to be an item requiring close attention.

This study was initiated to quantify the North American conditions in order to provide a base requirement on which to assess existing and projected BBC 3-phase A.C. traction motors. Because of the interaction between motor design and the other elements of the AC-DC-AC propulsion system, computer simulations were used to check if a given motor led to a satisfactory systems solution. In addition, existing locomotive and, especially, truck characteristics led to severe constraints on the motor design.

It was found that no known existing 3-phase motor could satisfy all the performance requirements when subjected to the constraints of existing locomotives. An adaptation, however, of a current motor could be suitable if a slight increase of wheel diameter were allowed.

Using this motor, an optimal layout was achievable for the overall AC-DC-AC system. Four air-cooled traction inverters connected in parallel would be sufficient to supply the required current to the motors for continuous operation of the locomotive at 28% adhesion with 4000 hp on 4 axles.

The motor places some additional requirements on the trucks. The coefficient of weight transfer must be limited to less than .43 and wheel diameter tolerances limited to no more than ± 1.5 mm with new wheels. The locomotive will require 1067 mm (42 in) wheels in order to maintain clearance to the rail. New axle designs will be required to mount the motor suspension and main gear. Transom changes to reduce weight transfer and provide clearance to the motor will be required on the present 4-wheel EMD truck.

Provision can be made in the final motor design to allow for truck suspension of the motor and return air ducting. The truck suspension would be important if the motor were to be applied later in a high speed passenger locomotive application. Return air ducting is practical with an induction motor and would reduce even further its sensitivity to extreme environmental conditions.

A form of "impedance matching" exists between the 3-phase A.C. traction motor and the inverter group that supplies it. A different winding configuration results if either the number of motors or the number of inverters is changed. The most important railway applications would be served by one motor mechanical design, one rotor construction but two different stator windings.

The performance requirements, locomotive constraints, and AC-DC-AC traction system factors have been summarized into a technical definition for the 3-phase A.C. traction motor.

2.0 BACKGROUND

The 3-phase A.C. squirrel-cage induction motor is very attractive for transportation applications because of its simple, robust construction with a minimum number of moving parts. With the availablility of solid-state power conversion equipment in the last few years, traction systems using this motor have become feasible.

Railway locomotives are considered a good application for 3-phase A.C. traction motors, because these motors will allow more tractive effort and power than now possible with D.C. traction motors while being more reliable under severe railway environmental and operating conditions. This has led to the design and construction of approximately 100 locomotives in Europe of various types and power equipped with 3-phase A.C. traction.

There is also interest in North America in the 3-phase A.C. motor as a traction motor for domestic locomotives. Because of the preponderance of diesel-electric freight locomotives in North American railway fleets, the interest largely centers on this application.

In a number of important respects this application differs from any now undertaken or planned in Europe. The higher North American axle loads compared to Europe mean significantly higher tractive effort requirements at the wheel. The generally smaller wheel size in North America places a limitation on the gear reductions available and leads to unusually high motor torque requirements.

The axle loading and typical North American track conditions create a severe vibration environment for the motors. Furthermore, locomotives must be designed to operate successfully in extremely diverse climatic zones (subtropical/arctic) and under severe weather conditions.

This study was launched with the support of the Transportation Development Centre for the purpose of defining these and other conditions bearing on a potential 3-phase A.C. traction motor application to North American diesel-electric freight locomotives. This study was designed to assess the feasibility of using one of the half dozen currently available BBC 3-phase A.C. locomotive traction motors in this application, and if this proved impossible, derive a conceptual design of a suitable new motor.

The study was to be sufficiently broad in scope that a determination could be made concerning the applicability of the resulting motor to a wide range of locomotive power ratings and to units from various manufacturers.

3.0 AC-DC-AC LOCOMOTIVE TRACTION SYSTEM

Traction motors are simply one component in an overall vehicle system having numerous mechanical and electrical interrelationships between the various components. A primary work objective of this study was to identify expected interfaces between the 3-phase A.C. traction motor and the remainder of the propulsion system, the locomotive, and the operating environment.

This was primarily accomplished by analyzing existing 3-phase A.C. locomotives in regard to their interfacing requirements. Consideration was given to possible deviations arising from North American conditions as opposed to those prevailing overseas.

3.1 DESCRIPTION

In order to function satisfactorily as a locomotive traction motor the squirrel-cage induction motor must be supplied from a variable-frequency/variable-voltage (or current) source. The layout of the power conversion equipment typically used by BBC to accomplish this on diesel-electric locomotives is shown in figure 1. The variation of voltage and frequency is carried out in one stage by means of a group of voltage source inverters. A reactor (Lv) is usually required at the output of the inverter group for smoothing of the motor current at low motor speeds.

It is normal BBC practice at the relatively low power level associated with diesel-electric locomotives to connect all the traction motors and all the inverters in parallel. Smoothing of the D.C. input voltage to the inverters is achieved by a reactor/capacitor bank (Ld, Cd) arrangement. In a diesel-electric locomotive the input voltage to the inverters is developed by rectification of the 3-phase A.C. output of the engine-driven main alternator, leading to the term AC-DC-AC traction.

The 3-phase A.C. traction motors will return energy to the inverters when the locomotive is in dynamic braking. Dynamic brake resistors (R_B) are provided in the intermediate D.C. circuit to dissipate this braking energy.

The traction motors will be mounted conventionally into the trucks using two suspension points on the axle and a nose mount from the truck transom. Torque transmission will be accomplished by single-reduction gearing. Figure 2 shows the general arrangement of wheelset, gear, and motor.

3.2 INTER-RELATIONSHIPS BETWEEN COMPONENTS

The following summarizes the major relationships occurring between the traction motor and the other components of the propulsion system and the locomotive.

3.2.1 Locomotive Power Considerations

Locomotive diesel engines are characterized by a maximum power rating which cannot generally be exceeded. Railway operations dictate, on the other hand, that the locomotive utilize its available power to as great an extent as possible. These two considerations result in the requirement that the propulsion control system accurately load the engine to the limit of available traction power for the widest range of practical locomotive speeds. This requirement is depicted in figure 3 in terms of a generalized tractive effort-speed curve for AC-DC-AC traction.

Speed V_{max} represents the maximum operating speed of the locomotive. There is no requirement to maintain locomotive power utilization beyond V_{max} and the tractive effort curve will fall off with the natural induction motor characteristic.

As locomotive road speed is lowered, increasingly higher values of tractive effort must be realized in order to fully load the diesel engine. Since the tractive effort has to be transferred through the wheel-rail interface, high levels of tractive effort place great demands on adhesion utilization.

For AC-DC-AC traction, a maximum working level of adhesion utilization μ_{max} will be assigned, based on adhesion studies and locomotive testing, and the corresponding locomotive tractive effort rating F_{rtg} at full engine power can be calculated from:

$$F_{rtg} = \mu_{max} \times W \times C \qquad (1)$$

whereby C represents the number and W the loading of the driven axles.

The locomotive speed V_{rtg} (minimum speed for full engine power) associated with F_{rtg} will be given by:

$$V_{rtg} = \frac{N \times \eta_T}{F_{rtg}} \qquad (2)$$

whereby N represents the maximum engine power available (to the alternator) for traction and η_T represents the cumulative efficiency of the entire power train - alternator/rectifier/inverters/traction motors/gears.

Axle loading and desired adhesion utilization values for AC-DC-AC traction have been established by railway operators. This implies that the North American diesel-electric freight locomotives will be characterized by one specific level of maximum per-axle tractive effort F_{rtg} and that only the minimum speed for maximum power V_{rtg} will be influenced when designing for locomotives of differing diesel engine power capabilities.

3.2.2 Motor Torque Requirements

Motor torque M_{rtg} is required in order to develop a tractive effort F_{rtg} at the wheel:

$$M_{rtg} = \frac{F_{rtg} \times d_o}{2i} \qquad (3)$$

Whereby d_o represents the diameter of the unworn wheel and i the gear reduction.

Since AC-DC-AC freight locomotives will be expected to work with exceptionally high levels of continuous tractive effort, a large gear reduction is desirable in order to hold down motor torque and hence motor size. The achievable gear reduction is, however, limited by clearance considerations in the truck.

The gear reduction i depends on the number of teeth on the main and pinion gears Z_1, Z_2 respectively (assuming a single reduction arrangement):

$$i = \frac{Z_1}{Z_2} \qquad (4)$$

The number of pinion teeth will be held to a minimum consistent with acceptable strength and long life in order to obtain a large reduction. The actual gear reduction will then vary in steps depending on the number of teeth Z_1 selected for the main gear.

From strength considerations an appropriate module m must be chosen for the main gear. The main gear diameter D (at the pitch circle) can be calculated by:

$$D = m \times Z_1 \qquad (5)$$

and will vary in steps with the number of main gear teeth. Large gear diameters, however, reduce the clearance between the bottom of the gearbox (the lowest solid structure, with the exception of the wheels, under the locomotive) to the rail top surface. This relationship can be visualized in figure 2 from which the following expression can be derived:

$$\frac{1}{2} [d_o - (D + a + c))] \geq b \qquad (6)$$

whereby:

d_o = new wheel diameter
D = main gear diameter at pitch circle
a = allowable wear on wheel diameter
b = clearance to top-of-rail from gear box bottom
c = tooth height, clearance in gearbox, gearbox thickness (all on diameter)

A large number of main gear teeth will also act to physically shift the centerline of the motor away from the axle. This reduces the need for hollowing out the motor next to the axle and allows the motor diameter to be increased. An appproximate relationship between the motor diameter d_m and Z_1 can be derived in the form:

$$d_m = m \times (Z_1 + Z_2) - d_w \qquad (7)$$

whereby d_w represents the axle diameter.

The motor diameter will, of course, be limited by the available installation length d_t in a given truck.

3.2.3 Intermediate Circuit Voltage

The intermediate circuit voltage is obtained by rectification of the alternator output voltage. The alternator excitation is controlled such that a stable D.C. voltage is available to the inverters independent of the D.C. current drawn. In the higher notch settings this D.C. voltage will have its maximum value and thus act to limit the maximum achievable motor terminal voltage to U_{max}.

It has been found that selecting the maximum intermediate circuit voltage in the range of 1000---1500 VDC allows a suitable overall solution for the system of alternator/rectifier, voltage-source inverters, and 3-phase A.C. traction motors on diesel-electric locomotives.

The motor terminal voltage characteristic against locomotive speed represents an important design parameter because of its influence on motor and inverter sizing. With the voltage characteristic reaching U_{max} at V_{rtg} as shown in figure 3 a somewhat over-rated motor design is obtained in order to provide sufficient motor torque at maximum speed.

If, on the other hand, the motor voltage were brought up more slowly with locomotive speed a different motor design would result requiring more motor current from the inverter group at low speeds than would be the case with the above solution. The cost, weight, and volume implications of this added current increment on the inverter group preclude use of this control strategy in this application.

3.2.4 Inverter Operation

Subject to the selection of an inverter control as discussed in section 3.2.3 the inverter will be required to have the voltage and frequency characteristics shown generalized in figure 4. There are two distinct operating areas separated by the locomotive speed point V_{rtg}.

For speeds below V_{rtg} the motor will be supplied with a frequency f formed by measuring actual locomotive speed, converting this to an equivalent frequency, and adding a fixed desired slip frequency f_2. The motor current (and consequently, motor torque) can be set to any desired level within certain limits by raising or lowering the output voltage since voltage and frequency can be adjusted independently in a voltage-source inverter.

Typically the ratio of U to f will be maintained constant at speeds below V_{rtg} to give a desired (relatively) constant level of motor current in response to a notch setting in the engineer's control stand.

The current produced by the inverter has real, reactive, and harmonic components. To keep down torque pulsations and additional motor heating caused by the harmonic components at low inverter frequencies (approximately 0.5 Hz at locomotive start, for example) the averaged voltage output waveshape of the inverter should be reasonably sinusoidal. This is accomplished by introducing a number of additional pulses into every half-wave of the output voltage.

At low locomotive speeds a large, indefinite number of such pulses is introduced. The inverter produces the pulses at a frequency f_T, and there is no synchronized relationship between f_T and f. The motor reactance is augmented by an external 3-phase reactor in order to provide better smoothing.

As the locomotive speed increases, the inverter pulsing frequency will begin to be synchronized to a multiple of the inverter output frequency (7, 5, or 3 pulses per half-wave). This essentially eliminates instabilities in the current output that would be encountered if free pulsing were continued at higher speeds.

It would also be inappropriate to simply raise the inverter pulse frequency f_T above a given limit f_{Tmax} because of the added commutation losses this would entail.

Above speed V_{rtg} the locomotive must be controlled on constant power. Since the inverter output voltage has been assumed to have reached U_{max} at V_{rtg} a slip frequency variation must now be introduced. At the relatively high inverter frequencies associated with this speed range, the pulse frequency is directly synchronized to the output frequency. When the output frequency exceeds a pre-determined value, the 3-phase reactor will be bridged by a contactor since the reactor smoothing effect is no longer needed. (figure 1) This eliminates the voltage drop associated with the choke (small voltage and current steps shown in figure 3).

3.2.5 Motor Speed

The motor speed n and the axle speed n_{axle} are related through the gear reduction i:

$$n = n_{axle} \times i \qquad (8)$$

A large gear reduction acts to increase motor speed for a given maximum required locomotive speed V_{max}: (neglecting mechanical slip)

$$n_{max} = \frac{V_{max} \times i}{\pi(d_0 - a)} \qquad (9)$$

New wheel diameter d_0 has been assumed reduced by the maximum allowable wheel diameter wear a in order to arrive at the worst case. Maximum motor speed is usually well under allowable maximum limits for squirrel-cage A.C. induction traction motors.

The inverter must be capable of supplying the output frequency corresponding to n_{max}. This will depend on the number of motor poles p according to: (neglecting electrical slip)

$$f_{max} = \frac{n_{max} \times p}{120} \qquad (10)$$

This frequency must be less than the allowable maximum inverter pulse frequency f_{Tmax}. Since each commutation action in the inverter results in power losses, avoiding an overly large value of f_{Tmax} is desirable. The dead time associated with the commutations will also reduce somewhat the voltage available to the motors at high speeds if f_{Tmax} is large.

3.3 INTERFACE WITH THE TRUCK

The traction motor will be expected to fit into existing locomotive trucks. The significance of the gear reduction in regard to motor torque and speed, truck clearances, and inverter frequency requirements was developed in section 3.2.2. The traction motor will, however, be influenced by other truck characteristics, as developed below.

3.3.1 Available Truck Space

Figure 5 represents a composite space envelope for EMD and GE conventional traction motors. The most desirable configuration for the 3-phase A.C. traction motor would envision a motor diameter suited to the smaller EMD truck space. The nose suspension would be adapted when the motor is used in a Bombardier or GE truck.

The availability of space for the axle suspension poses a special problem with this motor. It is not desirable to significantly hollow out the frame on the axle side of the motor. Since the clearance conditions developed in section 3.2.2 limit the amount the motor centerline can be pushed away from the axle, the provision of a large motor diameter dictates that the axle suspension may have to be on the outside ends of the motor. The use of a roller bearing-type suspension will be certain to result in an external arrangement because of the added space needed for bearings. In this case, the suspension bearing on the gearbox end of the axle will have to be incorporated into the gearbox.

3.3.2 Weight Transfer

Due to the displacement between the force application point and the top of the rail in most existing trucks, moments are established when a locomotive is pulling a train that tend to unload the leading axle of each truck. Moreover, the locomotive itself will be subject to a moment due to the displacement between coupler height and the force application point in the truck. Figure 6 illustrates the geometry involved for a 4-axle locomotive (exaggerated to show the truck and locomotive pitching when pulling a train).

Locomotive weight transfer characteristics are expressed in terms of weight transfer coefficients for each axle:

$$WT_i = \frac{\Delta Wi}{\bar{F}} \text{ for the i-th axle} \qquad (11)$$

whereby ΔWi represents the increase or decrease in weight acting on the i-th axle.

and $\bar{F}$ represents the nominal tractive effort available from an axle if weight transfer effects were not present.

Weight transfer coefficients for one 4-axle locomotive are presented in figure 6 and can be seen to be symmetrical about the locomotive center. Figure 6 also shows that the coefficient will vary greatly depending on the tractive effort application point in the truck and that the maximum values can be minimized if the force application in the truck is brought down to rail height.

The significance of weight transfer to traction motor design lies in the fact that the weight transfer coefficient, when multiplied by the nominal per-axle tractive effort $\overline{F}$, represents an effective increase or decrease in axle loading and, depending on the conditions at the wheel-rail interface, will result in differing loading of the various traction motors.

The force that can be transmitted through the wheel-rail interface $\overline{F}_i$ at a given axle is a function both of mechanical slip s_m between wheel and rail and the effective axle loading:

$$\overline{F}_i = \mu(s_m) \times W_{eff\ i} \text{ for the i-th axle} \qquad (12)$$

Whereby

$$W_{eff\ i} = \Delta W_i + W \qquad (13)$$

and

$$s_m = \frac{V \text{ wheel} - V \text{ locomotive}}{V \text{ wheel}} \qquad (14)$$

The adhesion characteristic $U(s_m)$ is known to vary widely depending on a number of factors. For purposes of illustration a characteristic typical of dry, clean track can be assumed and the nominal per-axle tractive effort $\overline{F}_{nominal}$ drawn in for a given axle loading. Weight transfer effects can then be seen to increase or decrease available tractive effort of the various axles because of the change in effective axle loadings. The "worst case" change is shown in figure 7 to be between the front truck leading axle and the rear truck trailing axle for a given force application point H.

With modern trucks and well-maintained rail, the adhesion characteristic should not be significantly affected by the locomotive speed or axle loadings. The same tractive effort vs. slip curve can therefore be used at every point on the desired tractive effort vs. speed curve. This is illustrated in figure 8 for a number of selected speeds.

The traction motor characteristic must now also be introduced into figure 7 order to solve for the respective motor loadings. The electrical slip s_e is defined by:

$$s_e = \frac{V_{synchronous} - V_{wheel}}{V_{synchronous}} \qquad (15)$$

whereby $V_{synchronous}$ is the locomotive ground speed that would result when power is neither transmitted across the wheel-rail interface nor through the motor air-gap.

Since, typically, in motoring

$$(V_{wheel} - V_{locomotive}) << (V_{synchronous} - V_{wheel}) \qquad (16)$$

portrays the fact that the induction motor usually has a much "softer" transmission characteristic than the wheel-rail junction and that because

$$(V_{synchronous} - V_{wheel}) << V_{locomotive} \qquad (17)$$

for all but the lowest locomotive speeds, s_e can be depicted on the same scale as s_m with little error.

The tractive effort intersection can be seen to vary in accordance with the tractive effort diagram. Electrical slip s_e will change in magnitude and slope in accordance with the inverter control.

The tractive effort slip behavior of the axles can be graphically determined for a particular motor as shown in figure 9. Three locomotive speeds are portrayed and a typical solution indicated for one of the speeds.

It is to the advantage of the inverter-controlled induction motor that at a large required tractive effort the motor characteristic is relatively flat. This considerably reduces the actual tractive effort difference between the lightest and most heavily loaded axles. The added increment of tractive effort, however, ultimately results in added current in some of the traction motors and must be considered in the motor design.

3.3.3 Wheel Diameter Tolerance

Unlike weight transfer effects, which are most pronounced at low speeds and high tractive effort, wheel diameter-related effects become most serious at higher speeds. Referring to figure 10, it can be seen that in the example shown unmatched wheel diameters will result in the larger wheels accepting more than their share of the overall tractive effort. The effect is on the same order of magnitude at low speeds as that arising from weight transfer.

At higher speeds the spread between the tractive effort produced by large-diameter and small-diameter wheels increases. Since the inverter attempts to control current to a constant value over the entire speed range of the locomotive the motors associated with the larger axles will experience larger than rated current. Since this additional increment of current occurs at speeds where the current loading of the motors has already become relatively high (figure 3) wheel size differentials must be considered in the design of the motor. A replacement wheelset cannot be used on the AC-DC-AC locomotive with a parallel motor connection unless it is first trued to the average diameter of existing wheels if a possible motor overloading situation is to be avoided.

4.0 REQUIREMENTS

4.1 LOCOMOTIVE PERFORMANCE

Locomotive performance requirements were derived primarily from discussions with a number of North American railroads. Comparisons were made with existing locomotives using conventional traction and performance criteria emphasized in areas where AC-DC-AC traction has significant advantages over conventional traction.

4.1.1 Locomotive Configuration

The overwhelming majority of locomotives in use in North America are diesel-electric units for freight service having the following physical characteristics:

- Bo-Bo or Co-Co truck configurations subject to various degrees of weight transfer.
- axle-mounted, nose-suspended traction motor suspensions
- hood and frame construction with a high, narrow hood and frame limited to approx. 21 m (69 ft) length.
- single cab with capability of travel in either direction
- gearing for high tractive effort and moderate maximum speed (120 km/h)
- maximum static axle loading range of 28 to 32 t (62,000 to 71,000 lbs.)

This locomotive type has evolved in North America for a number of practical reasons historically and must now be considered the standard configuration for North American railroading. The design of AC-DC-AC traction must be oriented to this existing configuration and its inherent limitations for reasons of acceptance by railroad authorities.

4.1.2 Power Capability

The future AC-DC-AC locomotive will be designed for an engine developing 4000 hp for traction into the alternator. For the purposes of a conservative motor design it has been assumed that the average power transmission efficiency will exceed 88% when mechanical power is measured between the input to the alternator and the wheel. The available rail horsepower is plotted in figure 11 as a hyperbola to approximate the above conditions.

The design of the traction motors will be based on a 4-axle locomotive whereby each motor will be expected to deliver approximately 880 hp to the rail. In railway terminology, however, the motors would be designated as 1000 hp machines for convenience of description.

4.1.3 Tractive Effort (4-Axle)

At the minimum continuous speed for full power V_{rtg} the AC-DC-AC locomotive will be required to work continuously at 28% adhesion, if available. This corresponds to a tractive effort F_{rtg} for a 4-axle locomotive weighing 118 t (260,200 lb) of:

$$F_{rtg} = .28 \times 118\ t \times 9.81 \frac{kN}{t} = \underline{324\ kN} \qquad (18)$$

by use of equation (1). The associated speed V_{rtg} is given by equation (2) as:

$$V_{rtg} = \frac{4000\ hp \times .746 \frac{kW}{hp} \times .88}{324\ kN} = 8.1\ m/s \qquad (19)$$

$$= \underline{29\ km/h}\ (18\ mph)$$

Conventional D.C. locomotives have typically been designed around an adhesion utilization of approximately 18 to 20% which has lately been increased to 25 to 26% for newer locomotive models. As can be seen in figure 11 a considerable continuous tractive effort advantage accrues to AC-DC-AC traction around speed V_{rtg} when compared with even the most modern 4-axle D.C. locomotives.

It is probable that the D.C. traction motors on conventional locomotives are being used at their maximum continuous current capabilities to produce the respective tractive efforts shown and would probably not be capable of further significant increase.

The D.C. traction motors in their series connection can produce a short-term tractive effort well in excess of that available continuously. The 3-phase A.C. traction motor shows a slight increase in continuous tractive effort at lower speeds as a result of improved inverter waveforms.

4.1.4 Tractive Effort (6-Axle)

For certain railroad operations 6-axle locomotives are preferred over 4-axle units since, at low speeds, 6-axle locomotives can deliver some 50% more tractive effort than 4-axle units for the same adhesion utilization. This relationship is not changed by the type of propulsion system involved.

Assuming 28% adhesion utilization, the required tractive effort and minimum speed for full power on a 6-axle AC-DC-AC locomotive weighing 177 t (396,000 lb) will be:

$$F_{rtg} = .28 \times 177t \times 9.81 \frac{kN}{t} = \underline{486\ kN} \qquad (20)$$

$$V_{rtg} = \frac{4000\ hp \times .746 \frac{kW}{hp} \times .88}{486\ kN} = 5.4\ m/s \qquad (21)$$

$$= \underline{19.4\ km/h}\ (12\ mph)$$

Although the specific power per motor has gone down from the 4-axle case the specific tractive effort has remained the same. In terms of mechanical construction the same motor design is applicable. The motor will be somewhat underutilized thermally in the 6-axle 4000 hp application.

Although some continuous tractive effort advantages may be realized for the AC-DC-AC drive in low speed drag service (figure 11) no particular advantage will be realized at higher speeds. Six D.C. traction motors can also easily handle 4000 hp and the larger locomotive frame associated with this number of axles can accommodate an engine of this rating.

The disadvantage of the 6-axle locomotive is that the extra 60 t of weight, while contributing to the tractive effort at low speeds, is of no use at higher speeds, where engine power limits are reached.

4.1.5 Motor Performance

The specific motor tractive effort as derived in sections 4.1.3 and 4.1.4 must meet or exceed 81 kN at V_{rtg} = 29 km/h for a 4-axle locomotive or V_{rtg} = 19 km/h for a 6-axle unit. Where possible, railways would prefer to run at speeds more in the range of the former than the latter in order to increase line throughput.

Since it is in this speed range that the 4-axle AC-DC-AC locomotive has the greatest performance advantages over D.C. traction V_{rtg} = 29 km/h will be the design speed for the 3-phase A.C. traction motor.

The specific motor tractive effort must be increased to account for truck-related effects. Trucks with exceptionally good weight transfer characteristics can attain overall locomotive weight transfer coefficients on the order of ±0.16. Force application points at coupler height, on the other hand, will result in weight transfer coefficients of approximately ±0.63.

Using the example in figure 6, the weight transfered at the nominal tractive effort shown is approximately 13%. The associated weight transfer coefficient, assuming 28% adhesion, would be ±0.46 a value corresponding to a truck design with some degree of emphasis placed on reducing weight transfer.

The tractive effort increase on the most heavily loaded axle in this example is on the order of 3 to 4%. Under marginal adhesion conditions where larger mechanical slip may be experienced the same nominal tractive effort may result in a solution intersection with a greater slope and, consequently larger overload factor (in the range 6 to 8%).

For puposes of motor design the 8% factor will be adopted. This will then require that trucks used with the standardized 3-phase A.C. traction motor have weight transfer coefficients of 0.46 or less.

In addition to this overload factor, consideration must also be given to the allowable tolerance in locomotive weight distribution. Typically the weight difference between an axle on one truck and an axle on another may reach 0.9 metric tons on 4-axle locomotives.

Wheel diameter differences between the various axles will also result in increased loadings for some traction motors. If a 3 mm diameter difference exists between wheels, approximately 10% tractive effort overload can be expected on the motor driving the larger wheels. Introducing the 10% factor into the motor design will require that wheels be maintained to within ± 1.5 mm of their nominal diameter. This compares with the currently allowed 6 mm difference on wheels on locomotive delivery.

4.2 ENVIRONMENTAL

4.2.1 Temperature

The 3-phase A.C. traction motor must operate satisfactorily in the most extreme temperature range encountered in its various possible North American applications. The range shall, however, be limited to those temperatures at which other locomotive systems or components are rated.

On the low temperature end -40°C will be the tentative minimum operating temperature of the motor. The maximum temperature limit will be defined as +43°C.

The torque available from a 3-phase squirrel-cage induction motor will vary markedly with motor temperature even when motor current and slip frequency are held constant for a given speed by the control system. To ensure the same locomotive tractive effort characteristic throughout the entire temperature range a temperature monitoring system usually is provided and integrated into the inverter controls.

The motor must have adequate cooling in order to continually operate at any point on the tractive effort diagram independent of the ambient temperature (in the above range) and engine speed. Forced air cooling by an external electric motor-driven blower will be used.

Continuous operation of the AC-DC-AC locomotive up to an altitude of 2000 m and at the maximum temperature cited above should be expected. Operation of the motor at maximum performance with 100°C ambient temperature for a period of 30 minutes may occur during tunnel operation.

4.2.2 Weather Conditions

The locomotive must operate continuously at all points on the tractive effort characteristic under all normal weather conditions experienced in North American railroading operations without damage or degradation to the motor. It should be expected that filters will not be used in the cooling air flow to the motors and that snow, moisture, and dust will be forced into the motor. Provision must be made for drainage on the underside of the motor such that water does not accumulate in the bottom of the housing.

It is expected that splash water will enter the motor when running the locomotive through areas with the rail under water. The motor design must consider that the motor may be partially or completely submerged and that it may be completely packed with snow. In these cases the design should attempt to minimize degradation and damage.

4.3 RELIABILITY AND MAINTAINABILITY

The period between scheduled major overhauls of the 3-phase A.C. traction motor will not be less than 9 years. This is based on operating mileage of approximately 200,000 km per year on typical North American main line track with 32 t axle loads. It is assumed that an axle suspension will be used with no springing at the motor support points on the axle.

The motor will be subjected to the temperature cycling typical for North American climate conditions and railroad freight service.

In the period between overhauls no more than 5% of the total population of 3-phase A.C. traction motors shall fail on the average in any year.

The traction motor will be installed and removed from the locomotive with the wheelset as a unit. Suitable provisions will be made to allow ready removal of the motor from the axle suspension. The pinion will have a hydraulic float-off feature and motor disassembly shall be possible without special tools or fixtures. Aside from the motor bearings there shall be no motor parts requiring inspection or replacement under normal conditions.

Where possible, the 3-phase A.C. traction motor should be applicable to existing widely-used trucks from all major North American manufacturers and usable with all modern engine power ratings.

4.4 FUTURE OPTIONS

The motor design should not preclude the adoption, in the future, of options leading to wider application areas for motors and/or added advantages to the railway operator.

4.4.1 Closed-Loop Cooling

The exhaust air from the 3-phase A.C. traction motors will not contain carbon or copper particles as is now the case with D.C. traction motors. This may enable return of the motor exhaust air to the cooling air supply system and partial reutilization. To the outside environment at truck level the motor will appear totally enclosed and will consequently not be readily subject to immersion and snow packing.

Reutilization of motor exhaust air would take place under low ambient temperature conditions. Depending on the actual cooling loop scheme adopted the following benefits could be expected:

- relatively constant component temperature for equipment in the cooling loop (reduces thermal stressing).
- reduced air filter clogging (if used).
- reduced blower power consumption.

The motor design must provide sufficient space at the end of the motor to allow attachment of an appropriate shroud for return of the cooling air.

4.4.2 Fully-Suspended Motor

If the 3-phase A.C. traction motor as defined in this study is to find application in the future to a possible high-speed passenger locomotive, the adoption of an appropriate motor suspension must be considered.

At speeds exceeding approximately 130 km/h it becomes increasingly important to minimize unsprung motor weight. The axle suspension can be retained if suitable resiliency is introduced into the supports or, alternatively, the motor may be truck-mounted.

In the case of the resilient axle suspension the main gear will also require springing from the axle. Attention must be given to the problem of gear alignment under worst-case dynamic conditions.

The resilient axle suspension can also introduce a torsional resiliency which will act to smooth momentary angular accelerations at the motor shaft due to track irregularities. The energy-storage characteristic of the resiliency, however, may make the wheel-rail interface more unstable when working in the desired mechanical slip region and therefore, is not desirable with induction motor drive.

The various forms of coupling truck-mounted motors to the axles generally allow free movement of the axles radially (vertically) and laterally while being extremely stiff torsionally. This would be considered ideal for a high-speed application of the induction motor.

5.0 STUDY RESULTS

As a result of examining the general interactions between components of a locomotive AC-DC-AC propulsion system, a number of relationships were established in section 3.2 that act as constraints on traction motor design. Further constraints were developed in section 3.3 in regard to interface with the truck.

The requirements on motor performance for an intended North American freight locomotive application were developed in section 4.1.

Computer simulations were used to determine if the performance requirements could be satisfied by existing motors subject to the constraints developed for North American conditions. It was found that a suitable design would result by upgrading an existing motor.

The simulations also led to a satisfactory electical system design.

Consideration was given to suitability of the traction motor to other locomotive applications. Modifications necessary for realizing various future options were also investigated.

5.1 SYSTEM SIMULATIONS

The system simulations were performed using the programmes developed by BBC over a long period of time for designing complete 3-phase A.C. traction systems. Various existing components (motors, inverters, smoothing chokes etc.) are already included in the software and can be called up as building blocks for any new application. Parameters can be varied (gear reduction, for example) and the motor performance checked against requirements.

The electrical variables common to the inverter group and traction motors can be analyzed to determine if an optimal system solution has been reached.

5.1.1 Motor Performance

Use was made of existing computer simulation programmes in investigating potental traction motors for their suitability in the North American freight locomotive application. Initial simulations were performed for 1017 mm (40 in) wheels and existing traction motors. A satisfactory system solution was not attained.

It was recognized that the tractive effort requirements for the 4-axle North American application exceeded available European diesel-electric locomotive 3-phase A.C. traction motor capabilities by a considerable margin. The small wheels limit the possibility of using large gear ratios to reach the required tractive effort.

A conceptual design was developed for an upgraded version of an existing motor and the design parameters introduced into the simulation program. A parametric analysis was carried out on wheel diameters to investigate available vs. required torque from this motor design. The results are shown in figure 12 and indicate that a minimum new wheel size of 1067 mm (42 in) will be required for a satisfactory solution.

The mechanical system quantities are summarized as follows:

- new wheel diameter	d_o = 1067 mm
- no. teeth main gear	Z_1 = 79
- no. teeth pinion gear	Z_2 = $(Z_2)_{min}$ = 16
- gear module	m = 10 mm
- allowable motor diameter	d_o = 720 mm (eq. 7)
- gear reduction	i = 4.94 (eq. 4)
- design adhesion	μ = .28
- design T.E. (locomotive)	F_{rtg} = 324 kN
- design motor torque	M_{rtg} = 8.75 kNm (eq.3)
- max. motor speed	n_{max} = 3174 rpm (eq.9)

The tractive effort characteristic shown in figure 11 will be satisfied in the speed range between V_{rtg} and V_{max}. Some additional tractive effort reserves will be available at low speed as will be discussed in section 5.1.2.

The traction motor will be configured with 6 poles. Using equation 10 this gives a maximum required input frequency to the motor of 157 Hz.

The motor will fit into the installation space for the EMD D-77 and GE 752 traction motors. The nose suspension in existing trucks may have to be changed when using the 3-phase A.C. motor because of the approximate 50% increase in reaction force at this point. In EMD trucks the existing nose suspension brackets will interfere with the motor and have to be relocated into the transom.

New axles with appropriate roller bearing suspensions, main gear, and 1067 mm (42 in) wheels will be required for any retrofit. Existing EMD 4-wheel trucks with high force application points may overload the traction motors under some conditions. New locomotives using AC-DC-AC traction should use low weight-transfer trucks to avoid this problem.

5.1.2 Electrical System Design

Initially five standard air-cooled 1000 VDC inverters were proposed for supplying the traction motors. It was found in the simulation work that the 5 units would not be fully utilized in this 4000 hp application.

Simulations were repeated with four units modified for slightly higher current ratings and this resulted in good utilization of the inverters throughout the entire speed range. The form of the motor current characteristic is depicted in figure 3.

Harmonic currents are reduced by the use of a series smoothing choke which is connected in circuit up to an input frequency of approximately 75 Hz. Depending on the pulsing control used, motor inductance, choke induction, and locomotive speed, some tractive effort increase is possible at low speed. There will be approximately 10% additional locomotive tractive effort continuously available at start and a possible additional 5 to 10% as a 1-hour rating limited by motor heating. These reserves will be, of course, over and above additional design torques required for truck-related effects and to account for tolerances between motors.

5.2 APPLICATION TO OTHER LOCOMOTIVES

Simulations were performed to investigate the use of the above 3-phase A.C. traction motor in a lower power 4-axle locomotive application and in a 6-axle 4000 hp application.

5.2.1 Four-Axle 3000 hp

If the complete AC-DC-AC traction system as developed on the basis of 4000 hp were operated on a lower-power locomotive no changes, other than control adjustments, would be necessary in the 3-phase A.C. traction equipment. The lower power locomotive would have the same tractive effort characteristic at low speed as the baseline unit. Above V_{rtg} (the new minimum speed for full power) the tractive effort characteristic would be limited by the available engine power.

For locomotives with electrical input power ratings to the alternator for traction of 3000 hp or less it was found that the inverter complement can be reduced to 3 units from 4. There would be cost, weight, and volume benefits resulting from this.

Since, in this case, the available inverter group output current will be decreased, a concomitant change will be required in the motor windings in order to produce the rated tractive effort at low speeds. Full inverter voltage will be reached already at V_{rtg} = 22 km/h (the new minimum speed for full power). The 3 inverters will be well utilized in this application. The rewound "standard" traction motors, however, will be somewhat underutilized thermally across the entire locomotive speed range.

5.2.2 Six-Axle 4000 hp

Since the baseline design situation envisions four 3-phase A.C. traction motors handling 4000 hp (input power to the alternator for traction) the use of 6 motors at the same locomotive power rating constitutes a relaxed application for the motors in regard to power-handling capabilities.

Using 6 "standard" traction motors instead of 4 will not result in increased tractive effort at low speed if the number of inverters is not increased. The locomotive would appear to have the tractive effort performance of a four axle unit although all 6 axles would be driven.

By rewinding the traction motors while retaining the same 4 inverters better utilization can be made of the available inverter output current. In this case, the minimum speed for full power will be approximately V_{rtg} = 20 km/h and the locomotive would outperform similiar 6-axle units having conventional propulsion at that speed.

5.2.3 Alternative Motor Winding

For the above applications a changed winding will be required for optimal system performance. Since it is desired that neither the rotor nor the mechanical structure of the stator be changed in the interest of keeping the motor standardized as far as possible the only change will be in the number of turns used on the stator winding.

Since changes to the winding are only possible in discrete steps it is forseen that the above two applications should be covered by one alternative winding arrangement. The inverter and alternator control would be appropriately adjusted to compensate for minor deviations of the actual attainable winding configuration from the theoretical optimum. Table A depicts the applicability areas of the base and the alternately-wound motors. The case of low power 6-axle units represents a considerable underutilization of the traction motor and was not considered in this study.

hp	4-Axle	6-Axle
2300-3000 hp	ALTERNATIVE	------
3100-4000 hp	BASE	ALTERNATIVE

TABLE A

APPLICABILITY OF 3-PHASE A.C. TRACTION MOTOR WINDINGS TO VARIOUS LOCOMOTIVE TYPES.

5.3 FUTURE OPTIONS

A conceptual mechanical motor design was developed establishing the feasibility of satisfying the performance objectives while fitting into existing trucks. It was established that closed-loop cooling and truck suspension of the motor were feasible under certain conditions.

5.3.1 Closed-Loop Cooling

The best mechanical motor layout results when the cooling air is introduced at the non-drive end of the motor. Provision for the closed-loop cooling must recognize, therefore, the extremely tight clearance situation at the exhaust openings caused by their proximity to the wheel. Although this is a matter for detailed investigation during actual motor design it is likely that the exhaust air feedback will take place in a duct built around and leading up from the gear-box. Air return to the frame will be by flexible boots as used with the inlet air.

5.3.2 Fully-Suspended Motor

As discussed in section 4.4.1, two alternatives are available for decoupling the traction motor from the shock environment at the axle. The provision of resiliency between motor and axle and in the main gear is one approach. The various resiliencies could be incorporated in the axle supension design and would not result in significant change to the motor center/axle center distance and could thus be carried out on either EMD or GE/Bombardier trucks.

A possible problem exists, however, at the gear tooth interface. The motor is free to make slight movements in a number of degrees of freedom and this may adversely affect the gear mesh.

A full suspension of the motor in the truck and torque transmission by cardan couplings eliminates the gear mesh problem. Such a suspension will increase the motor center/axle center distance considerably. The 3-phase A.C. traction motor could only be supplied with this suspension if a GE or Bombardier truck were used.

6. TRACTION MOTOR DEFINITION

The baseline locomotive has been defined in this study to be a four axle diesel-electric unit with a power input to the alternator of 4000 hp for traction. The design requirements and constraints on a standard 3-phase A.C. traction motor for North America have been developed for this locomotive and summarized in the following motor definition.

6.1 BASELINE APPLICATION

The baseline application for the standard 3-phase A.C. traction motor will be in a diesel-electric locomotive for North American freight service. The locomotive characteristics are as follows:

- Axle configuration:	Bo-Bo
- Axle loading:	28...32 t
- Power rating: (power for traction into alternator)	2400---4000 hp

The locomotive will have the following performance:

- Avg. transmission efficiency:	88%
- Min. speed for full power:	29 km/h
- T.E. at 29 km/h:	324 kN
- Max. speed (normal):	113 km/h
(overspeed trip):	120 km/h
- Full engine pwr. utilization:	29 to 120 km/h

6.2 ENVIRONMENT

The standard 3-phase A.C. traction motor will be designed to be suitable for conditions prevalent in North America as given in the following operating table.

- Temperature (for full performance):	-40°C --- +43°C
- Altitude:	2000 m
- Tunnel operation:	30 min. at 100°C and 2000 m altitude
- Cooling:	forced air (unfiltered)
- Contamination (in cooling air)	moisture, snow, dust, engine exhaust
- Splash water:	consistent with running 8 km/h through 5 cm of water over top of rail
- Impact:	motor to withstand ballast and ice strikes at 120 km/h in direction of motion
- Noise / E.M.I.:	motor will not generate objectional acoustic noise or electromagnetic interference at any locomotive speed or power setting
- Vibration/Shock	commensurate with 32 t axle loading, 120 km/h speed, and North American track conditions.

TABLE B

OPERATING CONDITIONS

6.3 MOTOR DESIGN

6.3.1 AC-DC-AC System

6.3.1.1 Inverter Supply

Motor shall be consistent with minimum number of power inverters for intended application, shall be designed for added heating from harmonic currents present, and be substantially free from torque pulsations.

6.3.1.2 Motor Terminal Voltage

Intermediate circuit voltage nominally 1000 VDC. Motor voltage determined by inverter pulse mode. Series choke to be used at low speed to limit harmonic currents.

6.3.1.3 Motor Frequency

Approximate maximum applied frequency 157 Hz. Motor torque shall be consistent with full power utilization of the locomotive engine at this frequency and below.

6.3.2 Mechanical Design

6.3.2.1 Torque

Motor torque shall be consistent with locomotive performance requirements under new wheel conditions and gear reduction of 79:16.

Torque reserves will be available on a continuous basis at start and low speeds subject to the maximum available inverter group continuous current rating at the corresponding motor frequencies or up to a maximum of 10% of the rated continuous torque, whichever is lower.

The rated continuous torque and torque reserves, if any, must be increased by an added increment to account for the following factors acting singley or in combination:

- weight tolerances and transfer
- unequal wheel diameters
- manufacturing tolerances and differing temperature between motors.

6.3.2.2 Structural Integrity

The motor shall withstand transient torque conditions arising from track irregularities and possible inverter commutation failures under any conditions of locomotive power, tractive effort, and speed without damage to the motor. For this purpose no special resiliences will be assumed in the motor suspension or the main gear.

The motor will withstand derailments without structual damage.

6.3.2.3 Maximum Speed

Maximum operating speed will be consistent with the locomotive speed trip, worn wheel conditions, and a gear reduction of 79:16. The motor will be provided with an appropriate speed sensing system. The motor shall not be damaged by wheel slip conditions resulting in motor speeds 20% above the maximum operating speed.

6.3.3 Cooling

The motor will be supplied with unfiltered cooling air from an external locomotive-mounted blower. The blower will be controlled independent of engine speed to give the air quality required for operating continually at any point on the tractive effort/speed characteristic. The cooling requirements shall consider the torque reserves and increments given in section 6.3.2.1.

The motor will be provided with appropriate temperature sensors.

6.4 TRUCK INSTALLATION

6.4.1 Existing Truck Requirement

The motor will be designed to fit into the composite clearance outline for EMD, GE and Bombardier trucks. The motor nose suspension will be a welded structure on the motor designed to mate with the GE/Bombardier transom suspension points. An alternate motor nose suspension will be available for mounting to (modified) EMD transom suspension points. In each case additional welded hook arrangements will be provided to retain the motor in the event of nose suspension failure.

New axles will be required for GE/Bombardier and EMD trucks, respectively retaining, where possible, the present journal arrangements. The motor cut-out, if any, will be based on the GE/Bombardier axle.

6.4.2 Axle Suspension

The axle suspension will be a bolt-on arrangement to the motor frame and utilize roller bearings. Different axle suspensions will result for GE/Bombardier and EMD trucks. The space required for this suspension will be co-ordinated with the motor design such that a satisfactory configuration results, in particular, in regard to removal/installation of the complete wheel set together with the motor and gearbox into or out of the locomotive.

6.4.3 Wheel Sizes

New wheels will be of 1067 mm (42 in) diameter with less than 3 mm difference between any two wheels on the locomotive. Wheels will be removed when their diameter becomes 990 mm (39 in) or less.

Replacement of a wheel set will require trueing to a diameter not less or greater than ± 1.5mm relative to the average of all existing locomotive wheel diameters.

6.4.4 Weight/Weight Transfer

Axle loading under static conditions will not vary more than ±0.9 t between axles.

Weight transfer coefficients will not exceed ±0.46 in the intended application by appropriate choice or modification of trucks.

6.5 MOTOR CONSTRUCTION

6.5.1 Material and Methods

The motor will be constructed of materials normally available in North America. Methods used in manufacture will be those normally employed in North America.

6.5.2 Applicable Standards

IEEE No. 11 - 1980
IEC Publ. No. 349 - 1971

6.5.3 Bearings

Appropriate for 32 t axle loading and 9 year minimum replacement life.

6.5.4 Insulation System

Appropriate for required performance, inverter power supply, cooling configuration, and 9 year minimum replacement life.

6.5.5 Reliability

There will be a failure rate no higher than 5% per year for the intended application of the 3-phase A.C. traction motor.

6.6 FUTURE OPTIONS

6.6.1 Alternative Locomotives

The motor will be designed taking into consideration other potential applications with the same level of specific torque but reduced specific motor power levels. An alternative motor configuration shall be possible for these applications whereby the only motor change will be a different winding on the stator. A building block approach will be employed to allow field assembly of the motor with either type of stator.

6.6.2 Closed-Loop Cooling

The motor design shall not preclude attachment of appropriate ducting at the exhaust end of the motor for possible future return of cooling air to the frame.

6.6.3 Fully-Suspended Motor

Consideration shall be given in the design of the motor frame to a possible truck suspension for the motor. There shall be provision structurally, if possible, for such truck mounting and the envisioned mounting areas for the roller bearing axle suspension shall not interfere with the future cardan couplings in the area of the axle.

7. CONCLUSIONS

This study has shown the overall feasibility of using 3-phase A.C. traction motors to meet the performance requirements of a future 4000 hp 4-axle diesel-electric locomotive. An appropriate motor is known to be derivable from a current design and would not present any serious difficulty to develop for the intended North American application.

7.1 SYSTEMS APPROACH

It is essential that the 3-phase A.C. traction motor be considered as a component in an overall system comprising the locomotive, trucks, inverter drive and controls, environmental conditions, and railroad operating and maintenence practices.

Computer simulations techniques were useful in arriving at an optimal electrical design in regard to overall system weight, volume, and cost. Mechanical considerations led to a number of important motor constraints.

7.2 BASELINE AC-DC-AC SYSTEM

The motor design will be based on a 4-axle 4000 hp diesel-electric locomotive application. It was found that providing the torque required for a high design level of adhesion utilization was more of a problem than the power-handling capability. No existing 3-phase A.C. traction motor could satisfy the tractive effort requirements when used with conventional North American trucks and wheel sizes.

Further simulation and analysis work, however, showed that a derivation from an existing BBC motor could achieve the required tractive effort characteristic. It will be necessary to use 1067 mm (42 in) instead of the common 1017 mm (40 in) wheels. There will also be constraints on truck weight transfer and wheel size differentials. The motor will fit into GE and Bombardier trucks and will be used with a roller bearing axle suspension. Use with standard EMD trucks is possible but will require significant modifications on the transom.

The baseline system was found to require 4 traction inverters of an upgraded, existing BBC design.

7.3 ALTERNATIVE LOCOMOTIVES

The AC-DC-AC traction system can be used in any 4-axle diesel-electric locomotive of 4000 hp or less without significant modification. At locomotive power levels of 3000 hp or less one of the traction inverters can be eliminated. If this is done, however, a motor stator with a changed number of turns will be required.

If, in the case of 4000 hp, it is desired to realize higher locomotive tractive effort at low speed by using 6 driven axles, a changed motor winding ratio will likewise be required.

All future mainline locomotive applications in the power range of 2300 to 4000 hp can be accommodated by the baseline and one additional winding ratio.

7.4 FUTURE OPTIONS

The motor conceptual design does not preclude the later adoption of a truck suspension for the motor in a high speed passenger engine application. Likewise, it may be possible to provide ducting of the motor exhaust air for routing back to the locomotive hood.

8. RECOMMENDATIONS

Further work on the North American 3-phase A.C. locomotive traction motor must be keyed to carrying out a program to use AC-DC-AC traction in North American locomotives. In the event such a program is launched, the first step will be to refine the motor technical definition into a specification.

A series of prototype motors would be built to this specification and subjected to extensive factory and locomotive testing. Since diesel-electric locomotives of 4000 hp on 4 axles do not currently exist, testing will have to be done in a compromise configuration.

The most critical testing area will be the ability of the motor to produce the required tractive effort at the wheel. This can be satisfactorily tested in any 4-axle high-horsepower unit.

The ability of the motor to handle its rated power (and hence its thermal capabilities) will require a supply of 4000 hp. This can be furnished by using a locomotive consist with interconnecting cabling or a 6-axle 4000 hp unit with only 4 axles driven.

Following verification of tractive effort and power capabilities the motor should be used in a long-term railroad application to gather operating experience. Additional motors may be useful for carrying out additional testing with such future-oriented options as truck suspensions and motor closed-loop cooling.

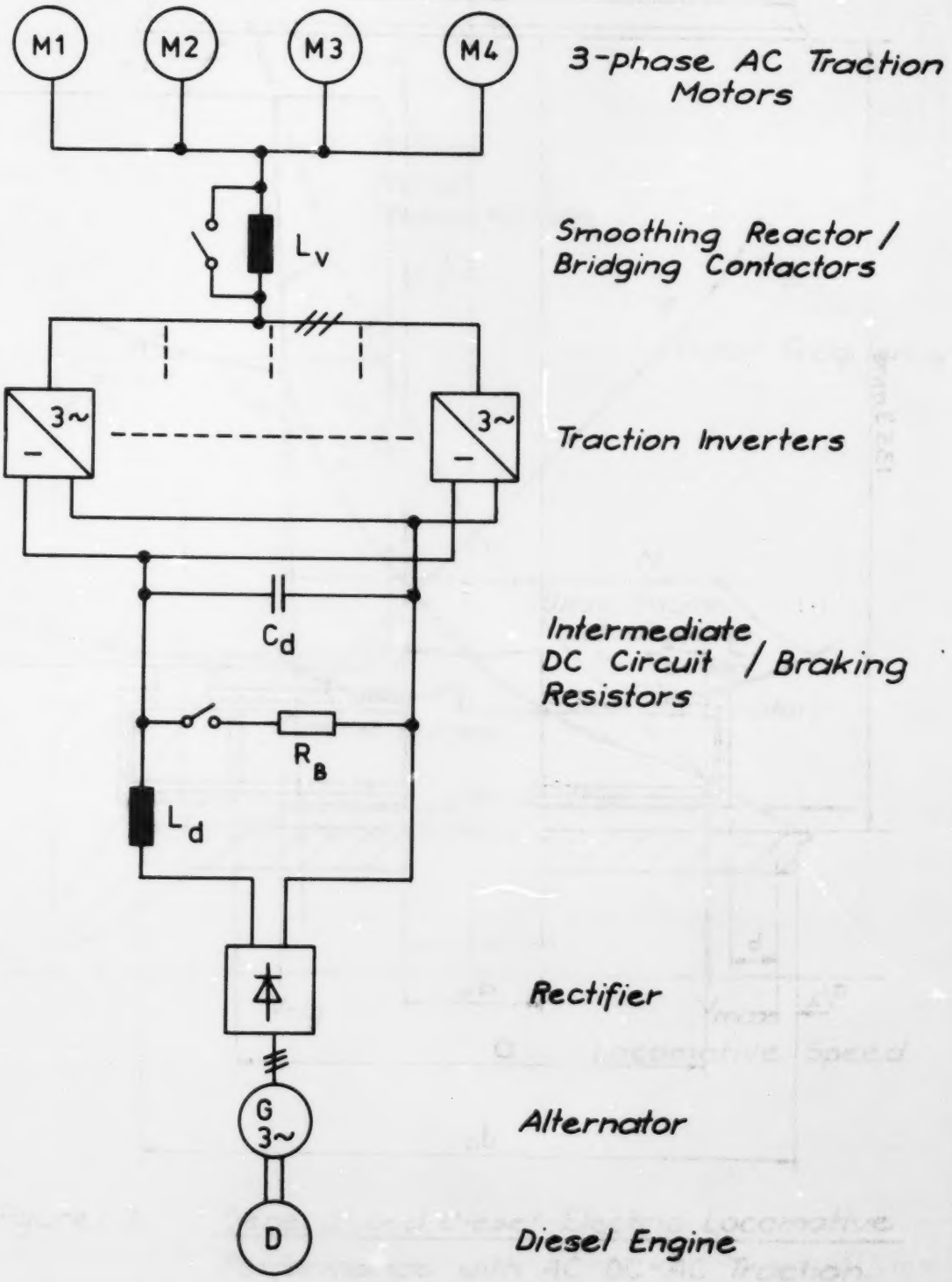


Figure: 1. AC-DC-AC Locomotive Traction System.

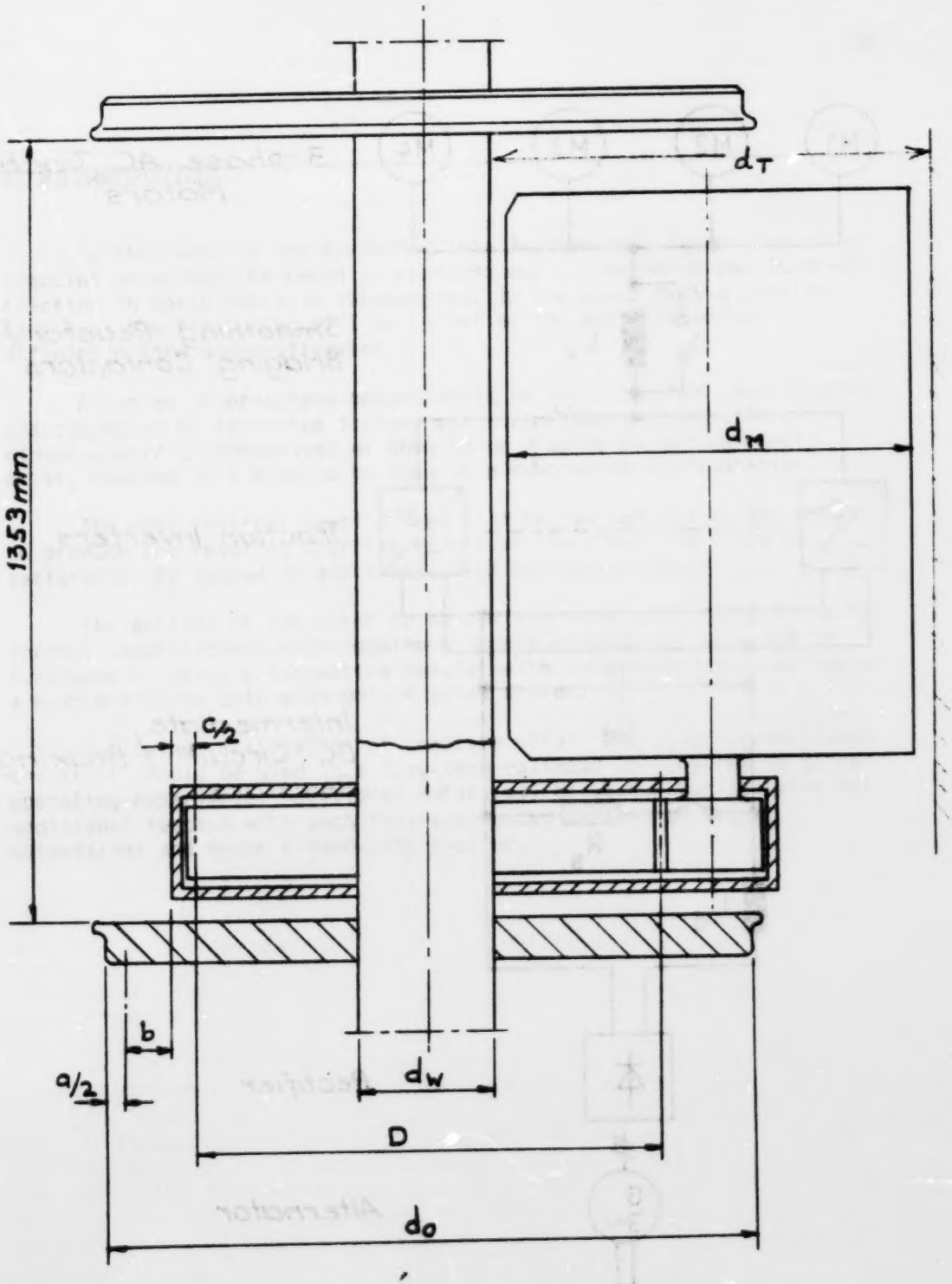


Figure 2 : TRACTION MOTOR INSTALLATION

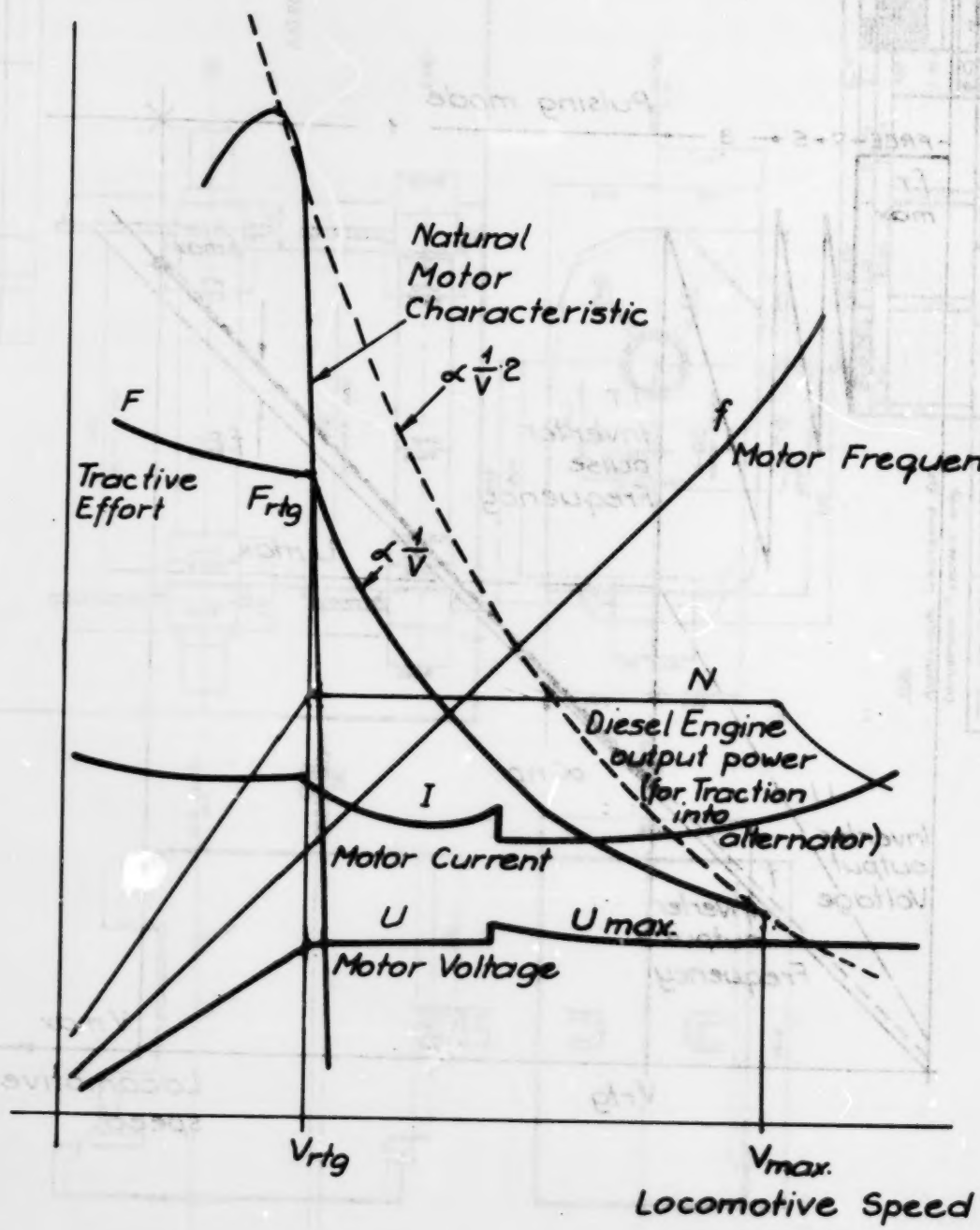


Figure: 3. Generalized Diesel-Electric Locomotive Performance with AC-DC-AC Traction.

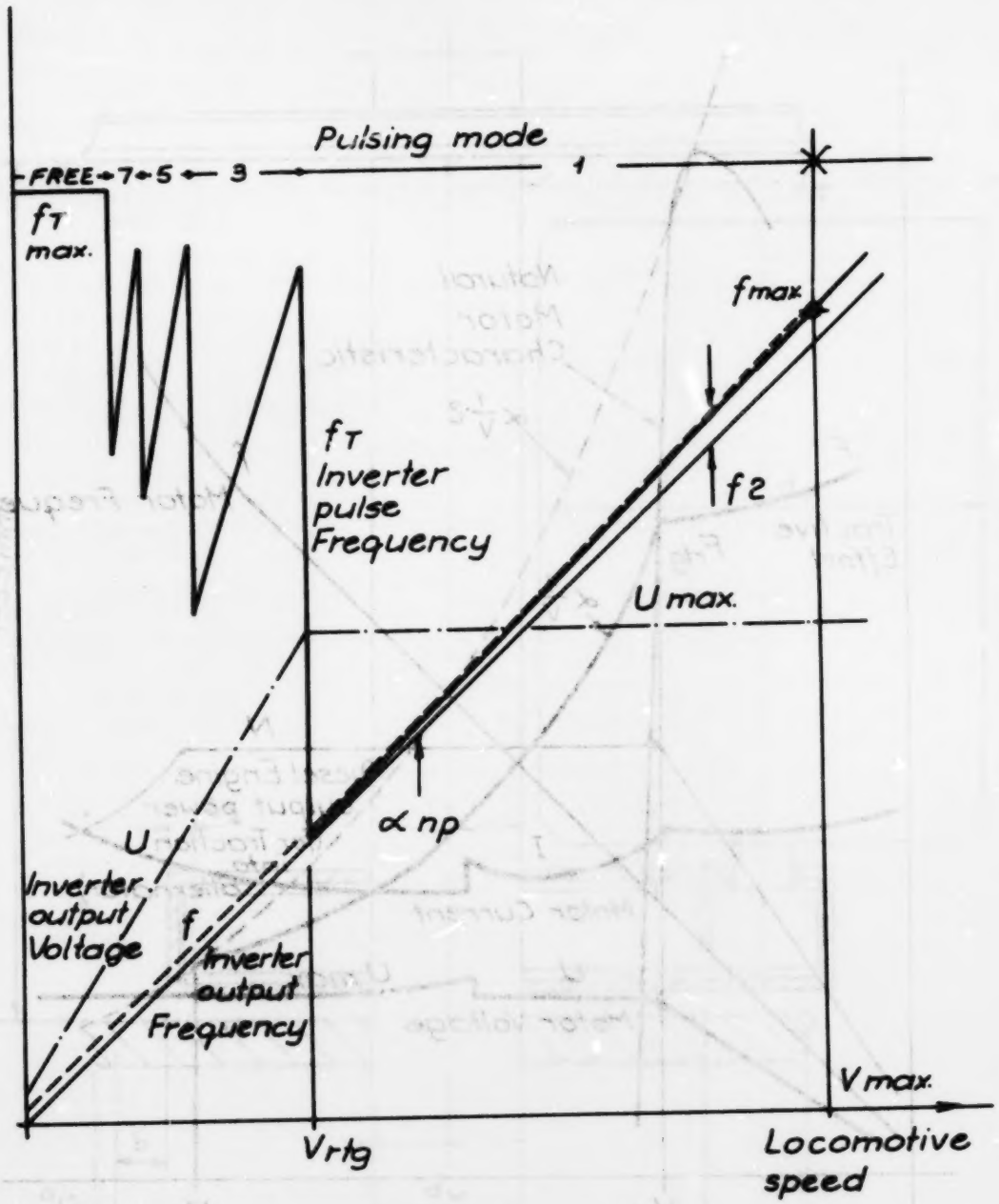
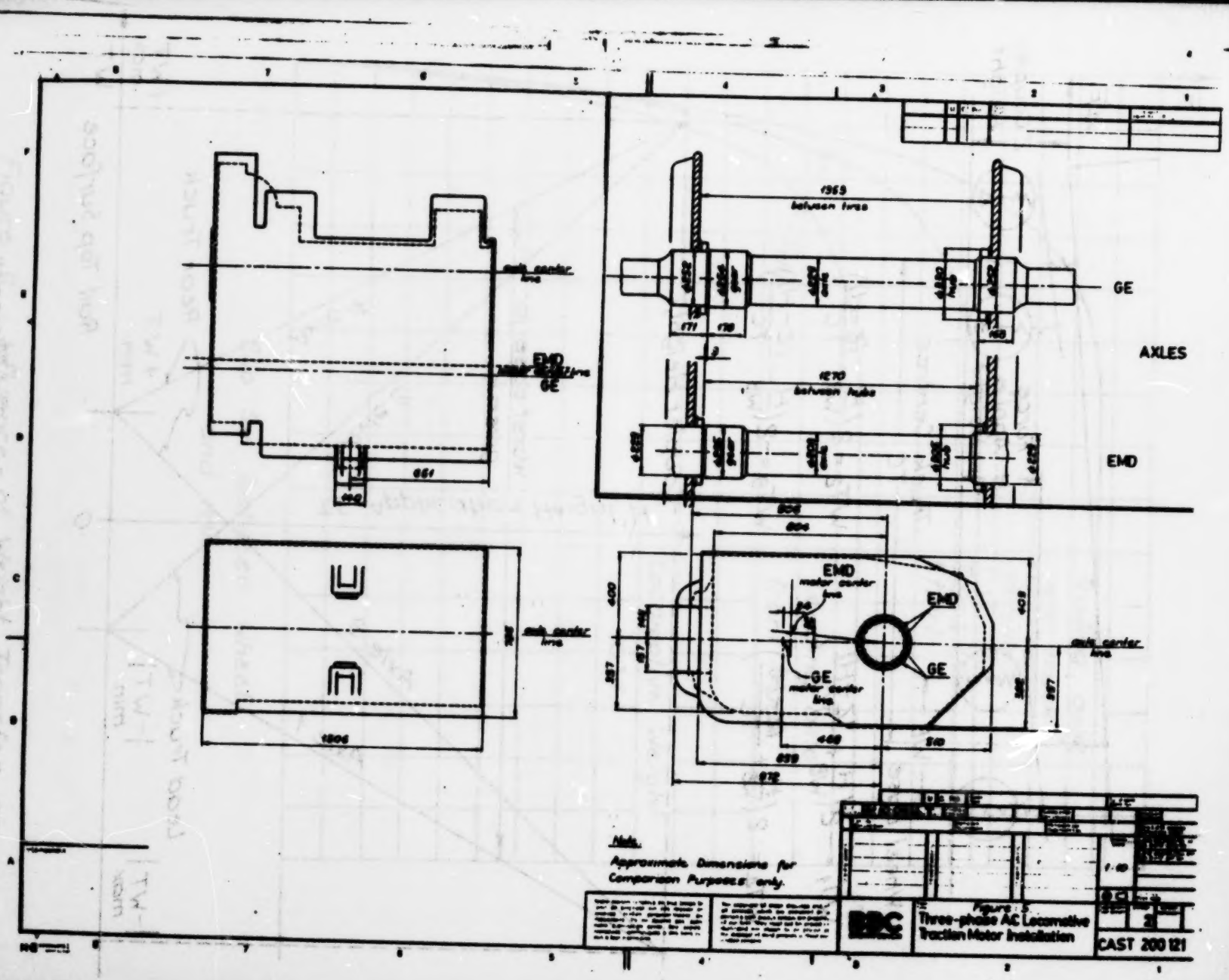
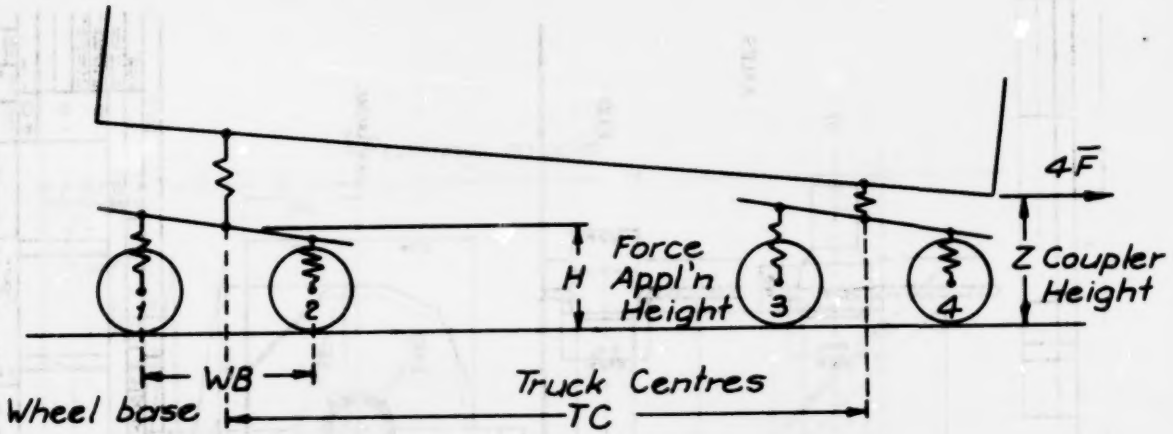


Figure: 4. Inverter Operation.


1969
between lines
GE
AXLES
1270
between hubs
EMD
EMD
motor center
line
EMD
GE
GE
motor center
line
axle center
line
Note.
Approximate Dimensions for
Comparison Purposes only.
Figure 2
Three-phase AC Locomotive
Traction Motor Installation
CAST 200 121



$$WT_1 = -2\left(\frac{H}{WB} + \frac{(Z-H)}{TC}\right) \qquad WT_2 = 2\left(\frac{H}{WB} - \frac{(Z-H)}{TC}\right)$$

$$WT_4 = 2\left(\frac{H}{WB} + \frac{(Z-H)}{TC}\right) \qquad WT_3 = -2\left(\frac{H}{WB} - \frac{(Z-H)}{TC}\right)$$

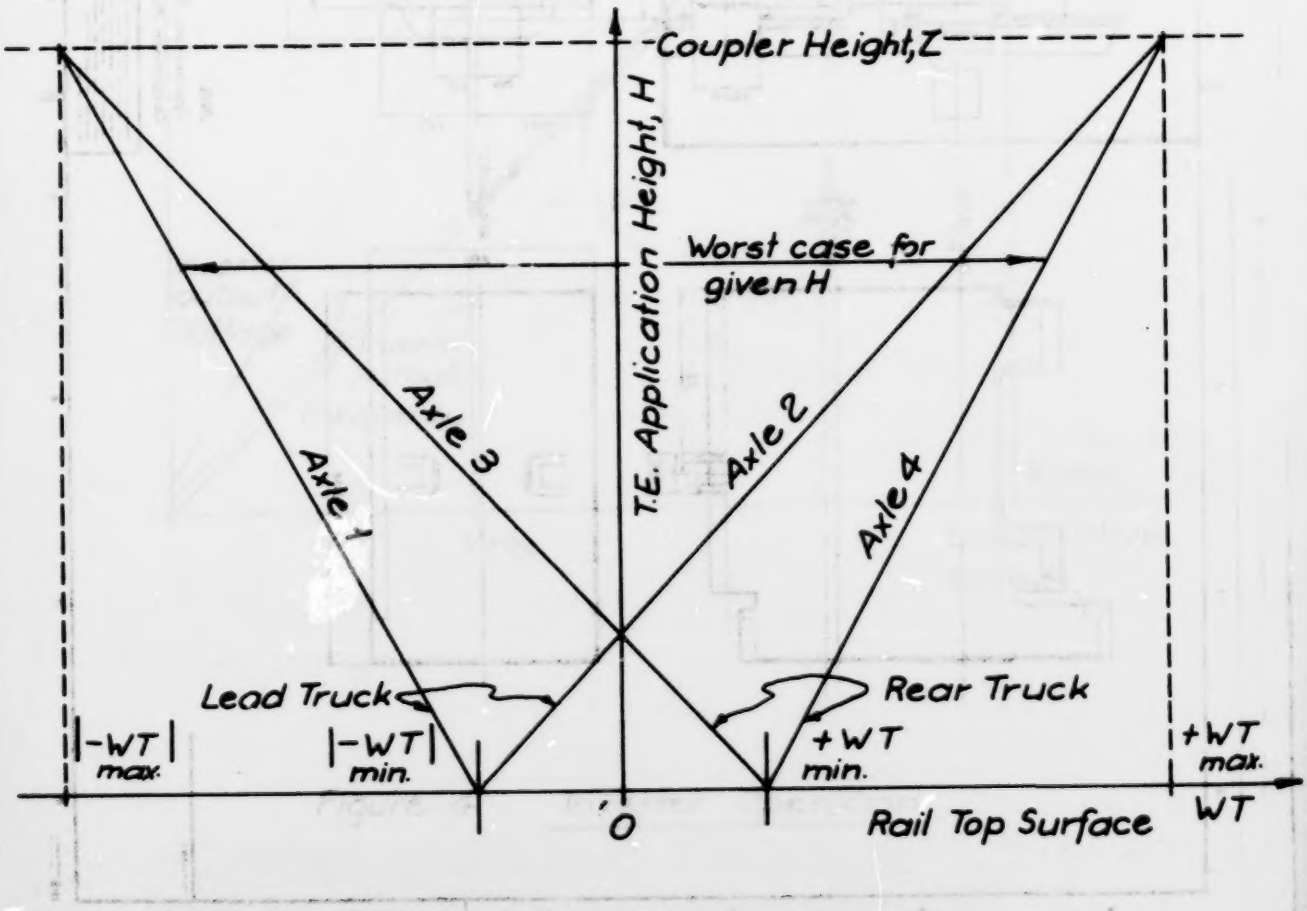


Figure: 6. Weight Transfer Coefficients.

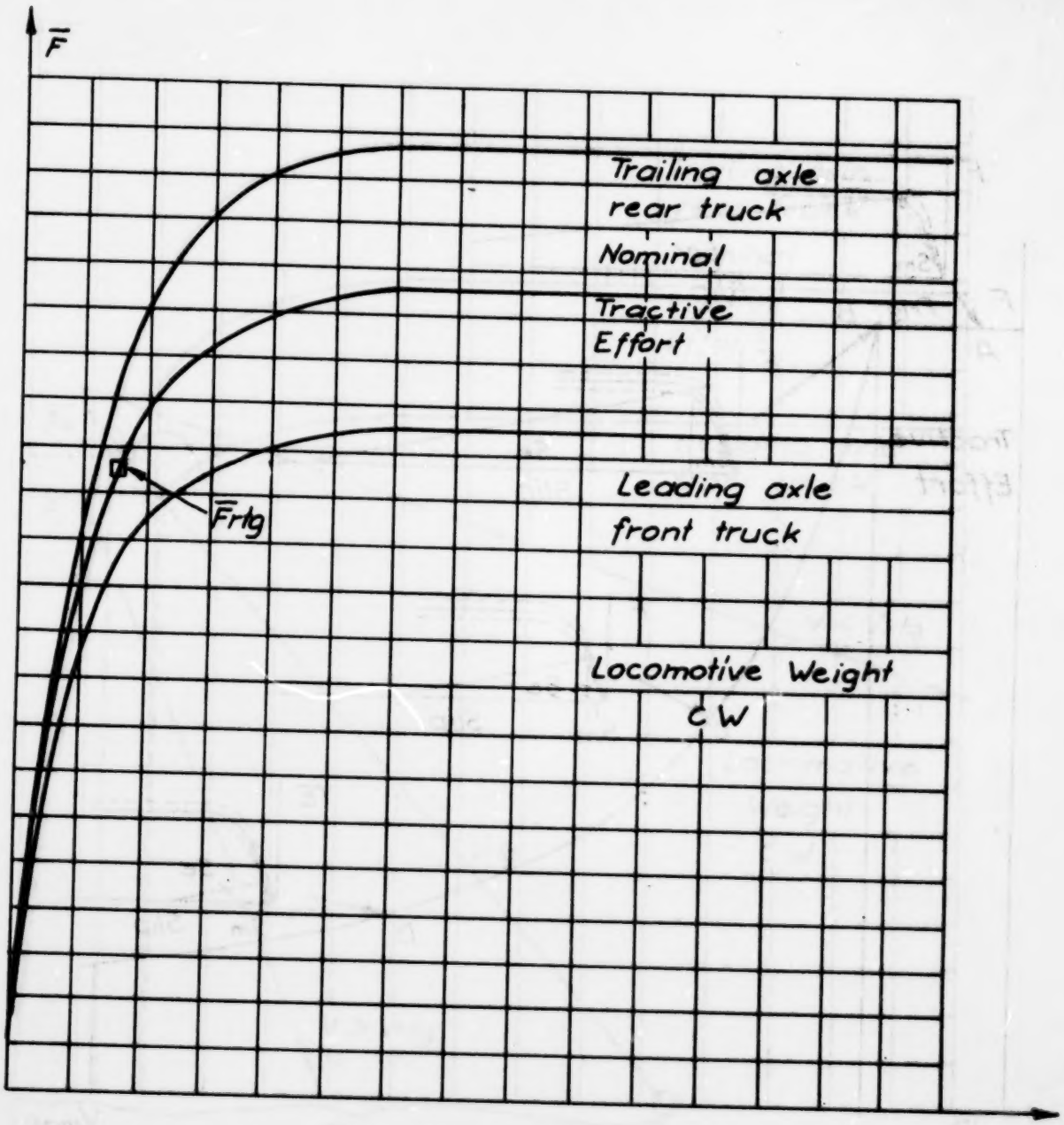


Figure: 7. Influence of Weight Transfer on Transmittable Force.

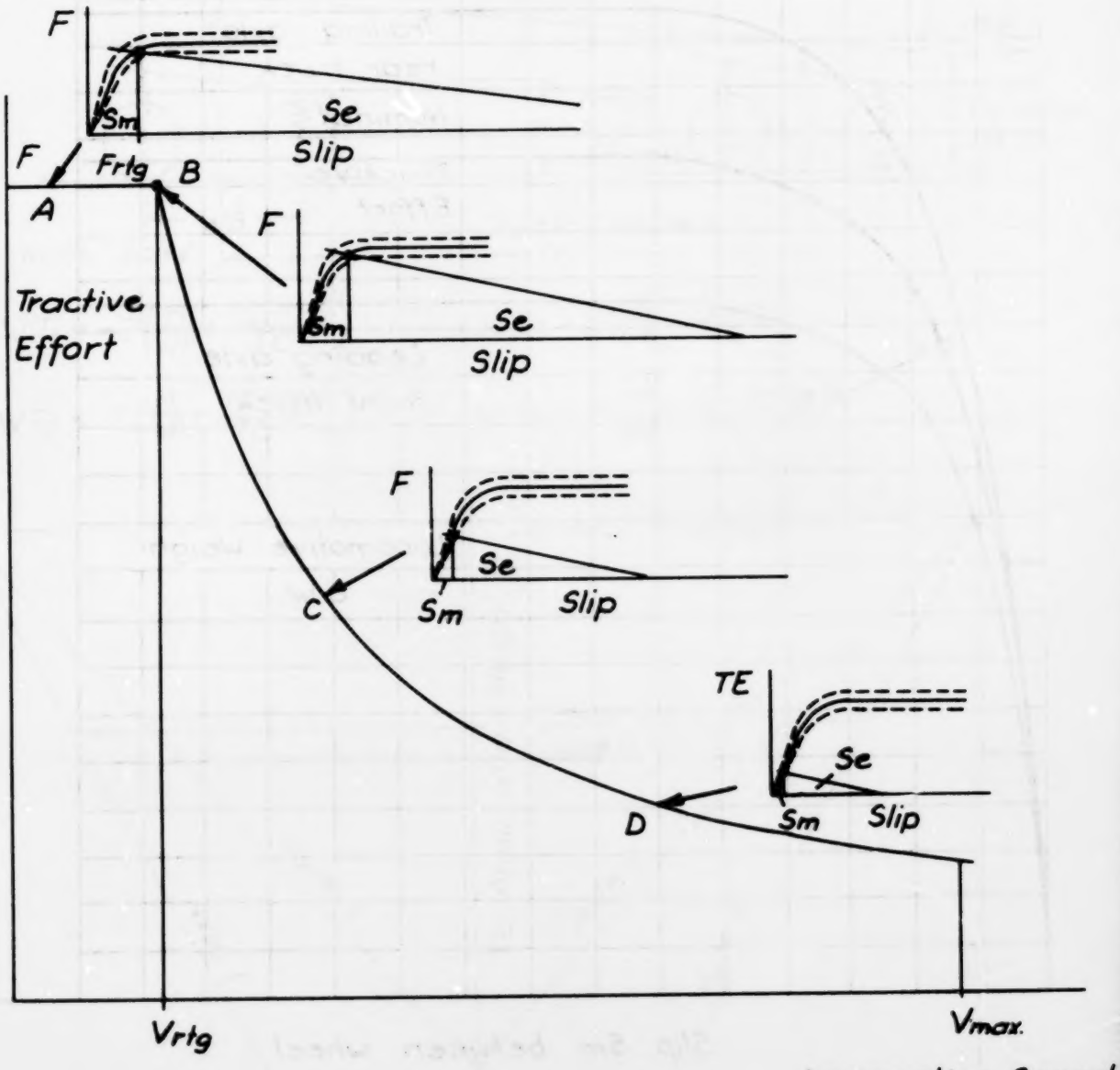


Figure: 8. Relationship Between Electrical and Mechanical Slip.

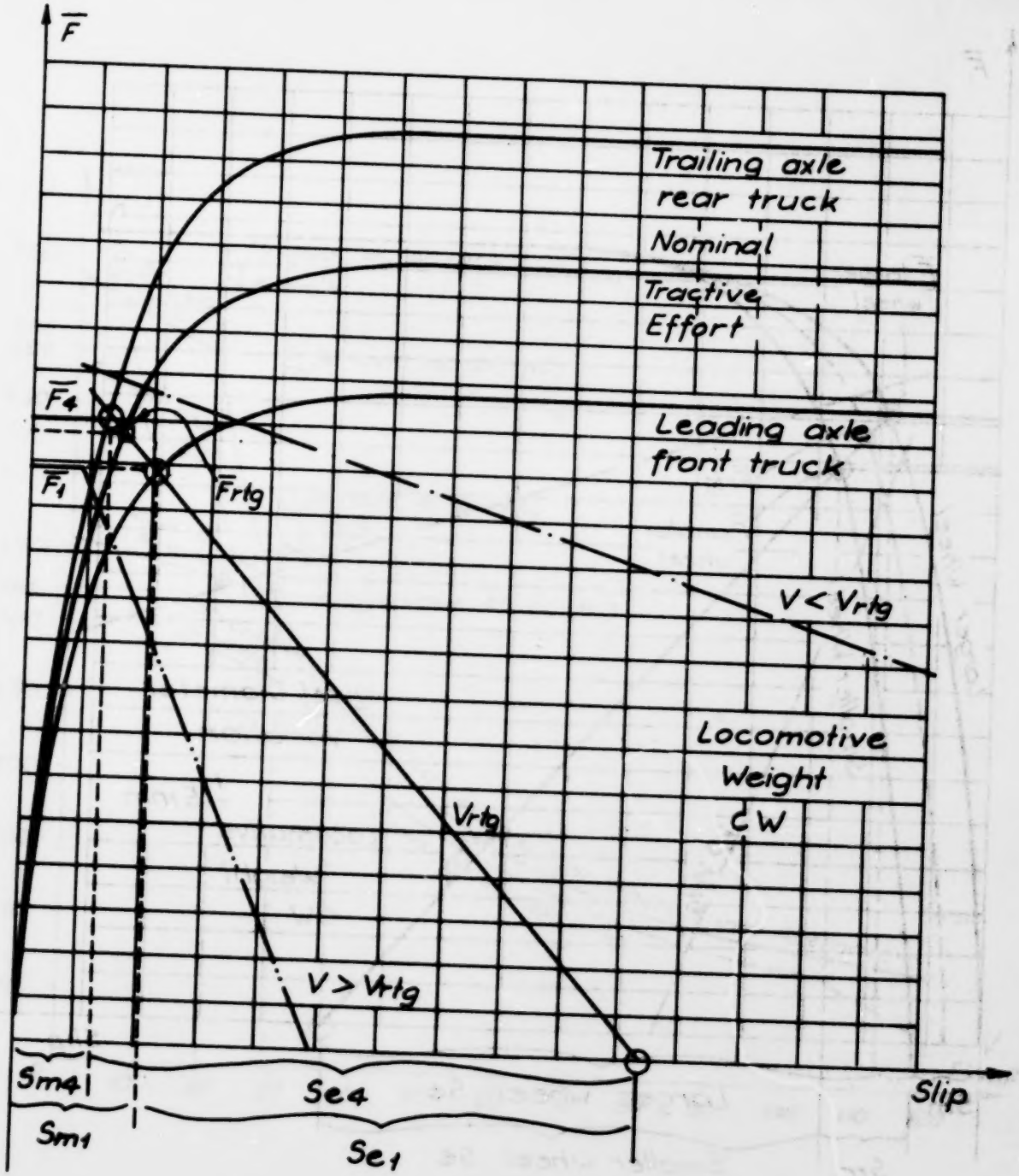


Figure: 9. Influence of Weight Transfer on Slip and Tractive Effort.

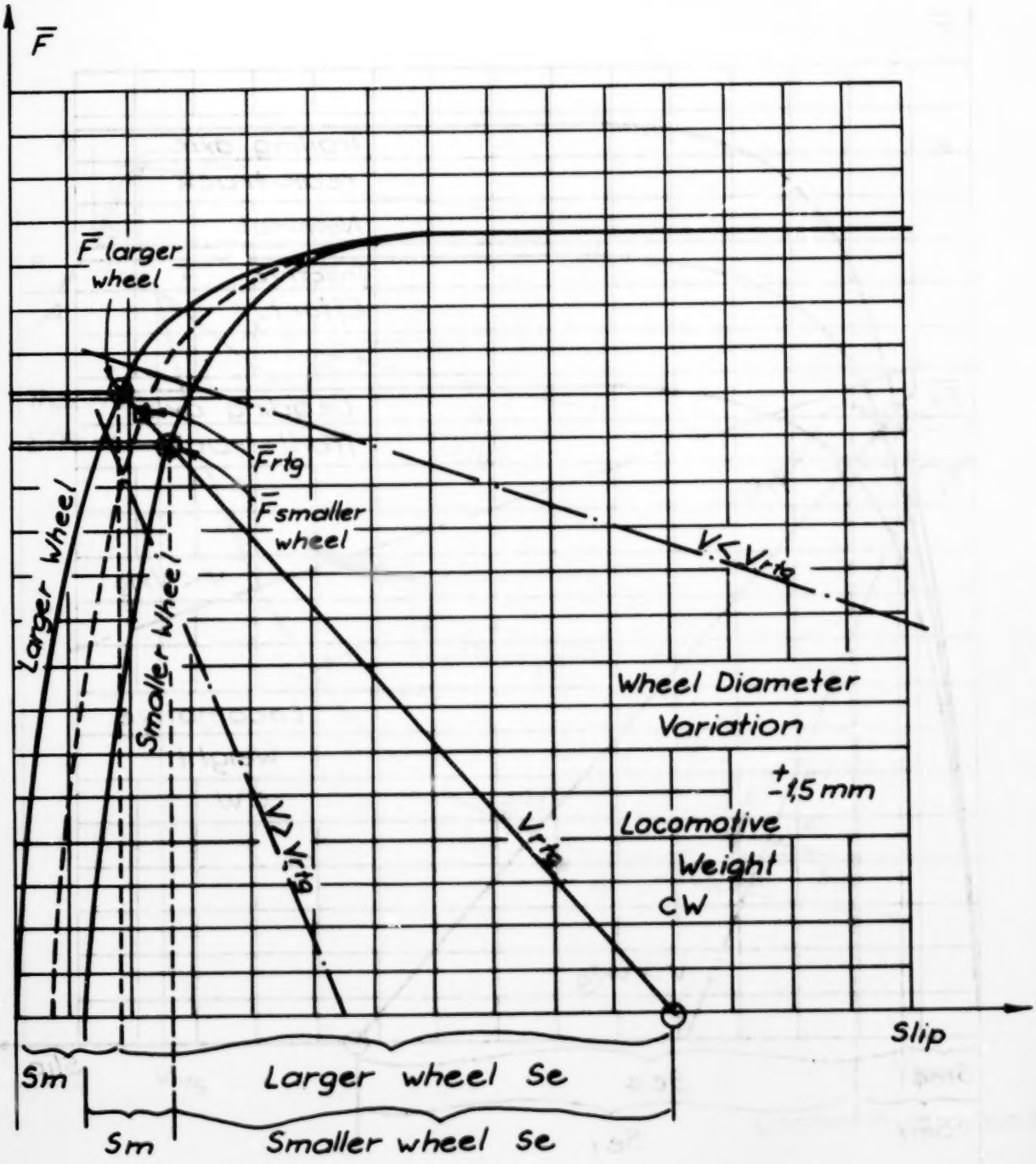


Figure: 10. Influence of Wheel Diameter on Slip and Tractive Effort.

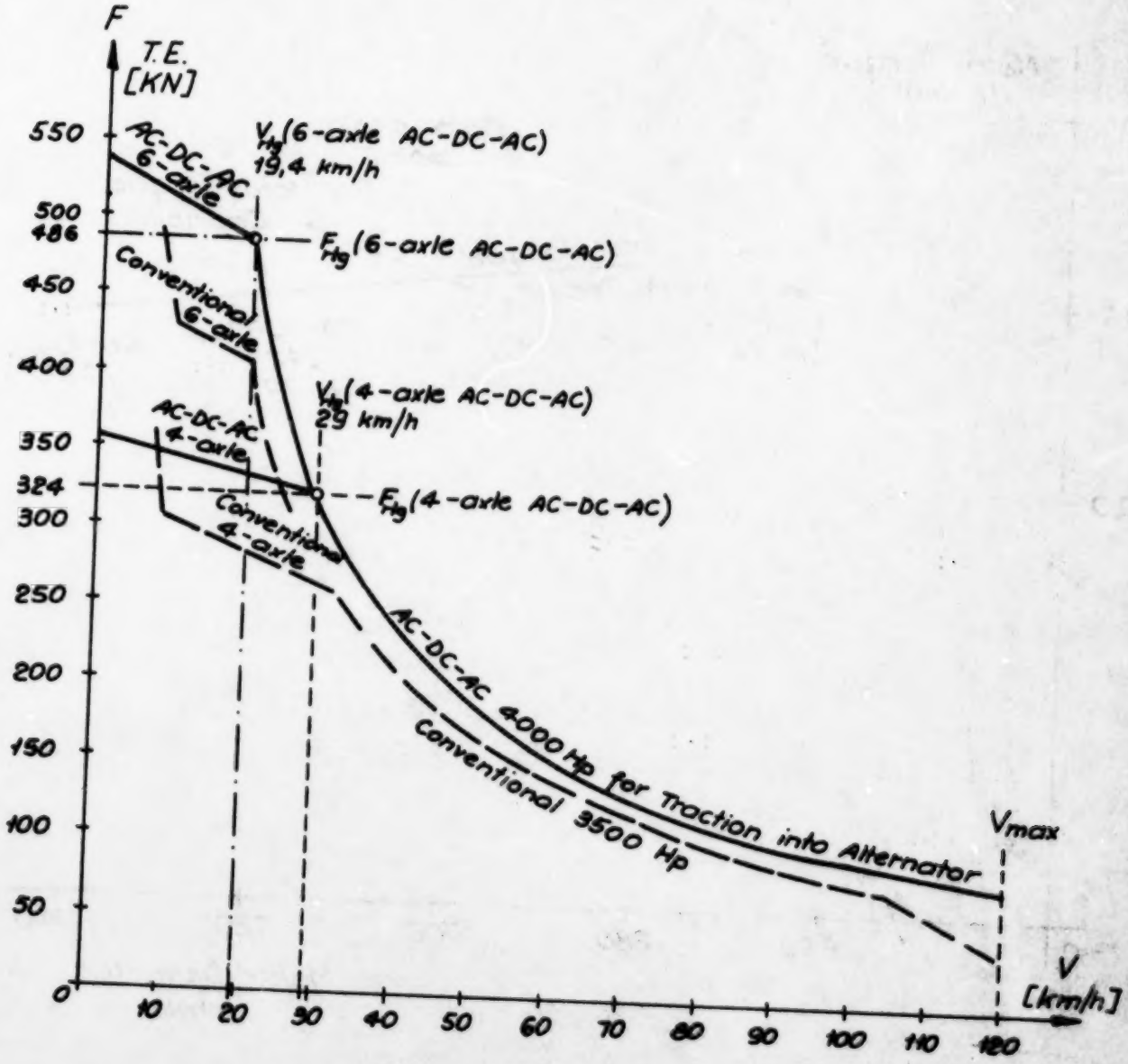


Figure : 11 AC-DC-AC Diesel-Electric Locomotive Performance Requirements.

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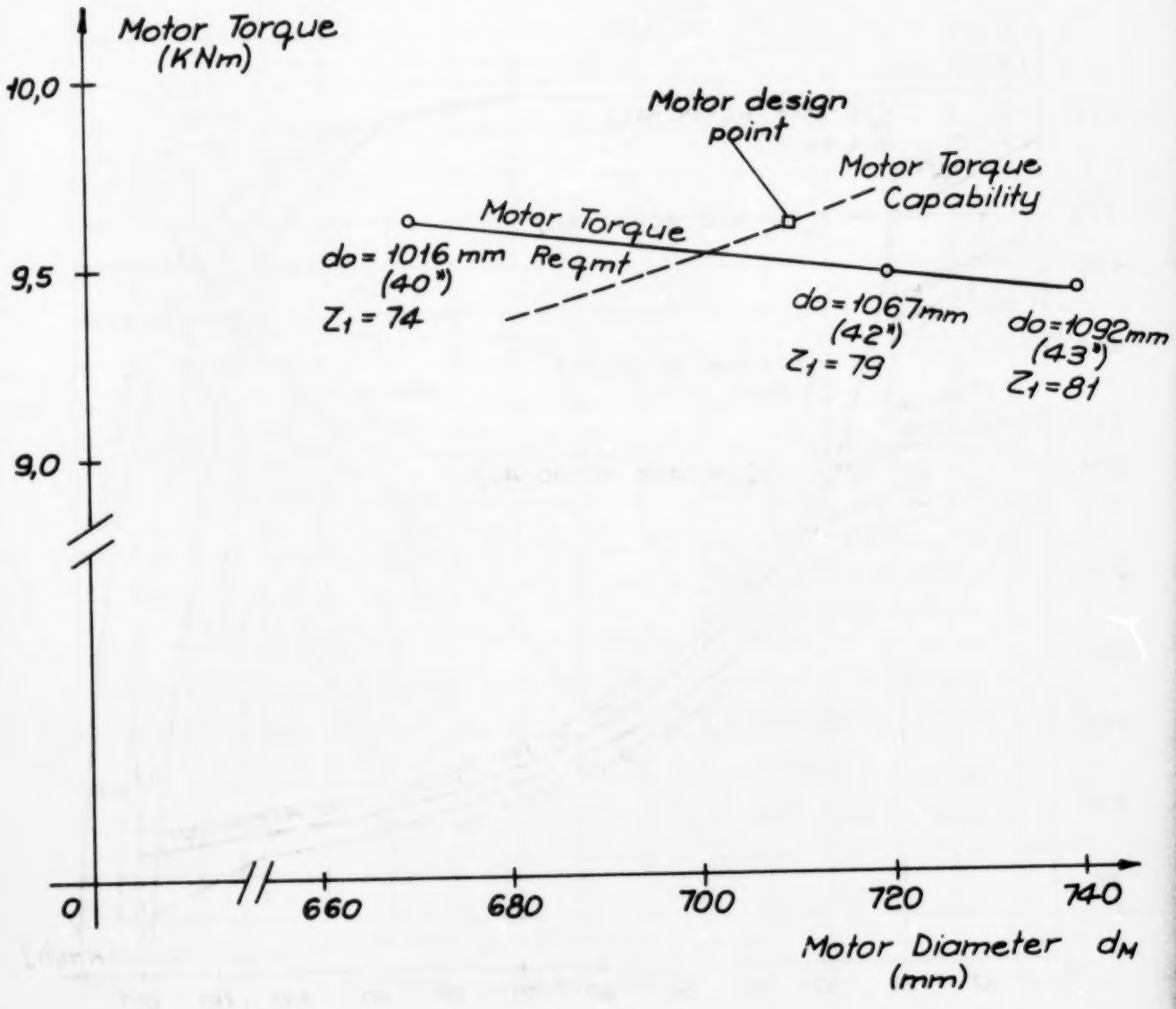

Figure : 12 Motor Torque Requirements and Capabilities Related to Wheel Size. [$V_{locomotive} = 0$]

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